Regional Projections of Climate Change for the Black Sea–Caspian Sea Area in Late 21st Century

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The results of dynamical downscaling of general circulation model *INMCM*4 data are described. *INMCM*4 model provided data on the atmosphere with 2 × 1.5° spatial resolution and on the ocean with 1 × 0.5° resolution. Two regional climate models (*RegCM*4 and *HadRM*3*P*) were used to downscale input data for 1971 – 2000 and 2071 – 2100 periods. Enhanced spatial resolution 25 × 25 km was obtained by downscaling procedure. Main parameters of climate change are presented for the Black Sea and Caspian region at the end of the 21st century assuming intense anthropogenic emission of greenhouse gases in accordance with *RCP*8.5 scenario. Climate change in the region, according to the models, is characterized by significant temperature increase in summer (~ 5 °C) and relatively moderate increase in winter (2 – 3 °C). The amount of precipitation is also considerably decreasing (more then by 40%) in the area that corresponds maximum warming (Carpathians and Anatolian peninsula) in spring and summer seasons. In both models total precipitation decrease occurs mainly due to decrease of convective precipitation frequency. Generally, the main reasons for predicted changes in the future climate are the thermodynamic phenomena connected with decreasing relative humidity as well as some circulation features caused by enhanced anti-cyclonic circulation in the region. Obtained numerical estimations of regional climate change are in a good agreement with data from previous studies.

Keywords: regional climate, simulation, the Black Sea region, Caspian Sea region

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Introduction. Global atmosphere-ocean general circulation model (GAOGCM) is the principal tool to study the climate of the 20th century and its possible changes in future under natural or anthropogenic impact. However, spatial resolution of the global models despite of their constant improvement is insufficient for reproduction of the atmospheric circulation regional peculiarities, connected with the underlying surface heterogeneity. One of the ways to specify the global simulation data with the purpose of climate changes reproduction within the regional scale (10 km and less) is dynamic downscaling.

Application of the regional climatic models with the increased spatial resolution is particularly actual for climate research of the Black Sea-Caspian region with its complex configuration of the coastal line, underlying surface heterogeneity and high mountains. In the existing global climatic models the Crimean Mountains have never been taken into the account, the Caucasian mountains peaks have not exceeded 2 km and the whole Black Sea has been determined by less than 10 points of the reference area. Consequently, the transfer from large scale global fields calculation to the regional evaluation is necessary to directly obtain the regional climate features (temperature, precipitation, humidity, wind velocity, etc.).

The growing quantity of papers is dedicated to the regional projections of climate changes. As per Europe, the most known projects are the following: *Forecasting the Regional scenarios and Uncertainties for Defining EUROPEAN Climate change risks and Effects* (*PRUDENCE*) [1], *Ensemble-Based Forecasts of Climate Changes and Their Impacts* (*ENSEMBLES*) [2], *Central and Eastern Europe Climate Change Impact and Vulnerability Assessment* (*CECILIA*) [3], *A Coordinated Regional Downscaling Experiment* (*CORDEX*) [4]. However, as a rule, the Black Sea-Caspian region went beyond the scope of the aforementioned calculations.

The papers [5, 6] describe numerical evaluations of the Black Sea region climate changes for the late 21st century applying *HadRM*3*P* regional climatic model [7] and *HadAM3P* large-scale atmospheric circulation model [8] with 200 km resolution. Space distributions of the temperature and precipitation changes in winter and summer periods were obtained. As the major results for the region, the considerable, exceeding the global indicators increase of climatic values of temperature in summer and to a certain degree lesser one – in winter was noted. It is accompanied by marked decrease of the precipitation in summer. The climate change evaluations for the Caucasus and Anatolian peninsula are given in the papers [9 – 11], although the Black Sea-Caspian region is situated at the border of the spatial domain (computational area) and it has been rather difficult to draw definite conclusions about climate changes in this region. In general the results of the aforementioned papers match the known climate change evaluations for Central and South-Eastern Europe. In accordance with majority of the models, warming in the European region will be going on more intensely than on the average on Earth [12, 13]. The increase of precipitation in winter is forecasted in Northern Europe and the decrease in summer – in Southern Europe. The persistent trend of summer precipitation decrease in the 21st century in the Mediterranean, Central and South-Eastern Europe, where the risk of summer drought grows, can be stated, based on the results of both global [12 – 15] and regional [16 – 20] models. At the same time there is no concerted significant change of the precipitation level [13] in the Central and South-Eastern Europe models for winter period. Possible causes of the precipitation level change are connected with increase of the temperature contrasts between land and ocean, shift of the large-scale circulation systems and back-coupled relations in *atmosphere-land* system [21, 22].

The present research covers the construction of climate change projections in the Black Sea-Caspian region applying two current models of regional atmospheric circulation with high spatial resolution – *RegCM*4, developed in the International Centre for Theoretical Physics (Trieste, Italy), and *HadRM*3*P*, developed by Met Office Hadley Centre, Great Britain within *Providing Regional Climates for Impact Studies* (*PRECIS*) Project framework. The results of *INMCM*4 model of the Institute of Numerical Mathematics, Russian Academy of Sciences were used as input data. This unique fourth generation model developed in CIS was included into the international project *CMIP*5 of comparing the joint global models [23].

Methodology. The aim was the recalculation of the data obtained from numerical models of atmospheric circulation with a rough spatial resolution, in the spatial grid with a higher resolution by using a numerical model that takes into account small-scale underlying surface features, missed in the initial global climate model**.** The results of the global simulations are applied as conditions on the lateral boundaries of the computational domain for regional climate models.

*INMCM*4 climate model [24, 25] consists of two main blocks – the atmosphere and ocean general circulation models. In the model of atmosphere three-dimensional equations of hydrodynamics in the hydrostatic approximation are solved applying the finite-difference method. Mass, moisture and angular momentum are conserved under the finite-difference scheme. The spatial resolution in the atmospheric module was 2 × 1.5°. There were 21 σ-levels vertically, time step was 5 min. The model includes parameterization scheme of radiation, deep and shallow convection, turbulent mixing in the boundary layer, and non-orographical gravity-wave drag, as well as the processes in the soil and vegetation [26].

In addition, *INMCM*4 model includes a block of general circulation in the ocean, being very important for maritime climate, in particular the one of the Black Sea region. Spatial resolution of this model is 1 × 0.5° longitudinally and 40 levels vertically. Time step is 2 hrs, wherein the inner step for advection of temperature and salinity calculated by the explicit scheme is 30 min. In the coupled model, heat, fresh water and friction stress fluxes are transferred from the atmospheric block into the oceanic one, and the surface temperature and sea ice area are transferred from the oceanic into the atmospheric block. Correction of the fluxes is not used.

Let us briefly note the features of the two regional models, applied for the *INMCM*4 data regionalization. *RegCM* version 4 regional climate model [27] is one of the contemporary models that are widely used for reproducing the climate in many parts of the world. It was applied in a number of international projects for the study of regional climate, for example, in the *North American Regional Climate Change Assessment Program* (*NARCCAP*) [28]. The basis of the regional model is the finite difference scheme for solving nonlinear three-dimensional equations of atmosphere thermohydrodynamics in the hydrostatic approximation. The explicit scheme with time splitting is applied. Its formulation was not changed significantly as compared to the previous version of the model [29, 30]. Staggered Arakawa *B*-type grid and vertical σ-coordinates were used. 18 vertical σ-levels are presented in the model, its spatial resolution is 25 × 25 km and time step is 1 min. Dynamic scheme of the regional model corresponds to the widely known mesoscale model *MM*5 [31], actively used in MHI for operational weather forecasting in the Black Sea region (http://hydrophys.ru).

In *RegCM* model a set of modern subgrid (i.e. not explicitly resolved for the model grid) parameterization schemes of physical processes is applied. To calculate some of the processes several alternative schemes can be used. A configuration of the parameterization schemes recommended as the most suitable for the majority of regions was selected. For the parameterization of turbulent mixing in the boundary layer of the atmosphere a modification of the scheme with non-local closure is applied [32]. Processes of the cumulus convection and convective precipitation are calculated according to a mixed pattern: following the recommendations of the developers [33], the scheme [34] with closure [35] over the land and the scheme [36] over the sea were selected. Large-scale cloudiness and precipitation are parameterized according to the method proposed in [37]. The basis for the cloudiness scheme is the traditional diagnostic approach when the proportion of the cells occupied by clouds depends on the relative humidity. The calculation of the large-scale precipitation takes into account the processes of accretion and evaporation of raindrops. For the parameterization of radiation fluxes in the *RegCM*4 model the adapted scheme of the *CCM*3 global model is applied [38, 39]. The concentration of radiation-active gases, water vapor and cloud cover are taken as an input parameter values. The model also includes a parameterization scheme of the processes in the top layer of the soil *Biosphere-Atmosphere Transfer Scheme* (*BATS*) [40]. According to this scheme the amount of snow, temperature and moisture content in the soil are calculated.

The second regional model is *HadRM*3*P* [7]. It is also formulated in the hydrostatic approximation. It has 19 hybrid vertical levels [41]. A *B*-type grid (under Arakawa classification) common for atmospheric models (the same as for the *RegCM*4 model) is applied for sampling of the equations horizontally.

*HadRM*3*P* model includes 4-level scheme *Met Office Surface Exchange Scheme* 1 (*MOSES* 1) [42] of the process parameterization in the upper layer of the soil. According to this scheme temperature and moisture content in the soil with regard to its type and properties, as well as the dominating type of vegetation are calculated.

Immediate data assimilation of the global model in the calculation procedure is carried out in the buffer zone (within the region borders). For both models, the assimilation is performed by adding relaxation terms to the primitive equations. As a result, the values of variables in the buffer zone are approximated by a linear combination of solutions of equations of regional forecasting models at the next time step, and the values obtained from a large-scale model. Thus, the *INMCM*4 data were applied as the boundary conditions on the outer domain border of the regional models. The initial terms within the computational domain were the same *INMCM*4 data, interpolated to the fine grid model at each vertical level. The *INMCM*4 data of the ocean block were used to set the temperature of the water surfaces. In the process of calculation the aforementioned data were also interpolated from the grids with 1 × 0.5° initial resolution on the finer sea grid.

To design the climate change projections, the time slice approach had been applied. Changes in climatic characteristics were calculated as the difference between the values of two periods, each having 30 year duration. For 2071 – 2100 year period the parameterized schemes of the model take into account the changes in the concentration of greenhouse gases (CO_2, CH_4, N_2O, O_3) and sulfate aerosol underone of the common scenarios of greenhouse gas emissions – the "adverse" *RCP*8.5 scenario [43]. As for the 1971 – 2000 year control period, the concentrations were set according to the observations.

The statistical significance of the obtained differences representing changes in climatic variables averaged over a 30-year future period in relation to the reference period, was assessed using the standard Student’s *t*-test, determined as a relation between obtained differences and root mean square variations of the variables themselves. In our case, the monthly averages of meteorological parameters for the selected seasons had been applied. A 10 % level of significance was chosen. In addition, the obtained values of regional climate change were considered concerted with the two regional models, if for each of them the absolute difference between the model and the average value for the two models does not exceed 30 %.

Validation is the most important stage in application of the regional models. As a rule, regionalization of the known reanalysis data and assessment of the water and heat balance consistency is carried out for this purpose [44]. Both models had been proved to be suitable for the study of climate change on a regional scale [45, 46].

The results. The attention is focused on the change fields of surface air temperature and atmospheric precipitation as the most important meteorological variables from a practical standpoint.

Air temperature. We should start from the features of large-scale surface air temperature changes in a future climate. In Fig. 1, a, b spatial distributions of air temperature changes at a 2 m. height, under the *INMCM*4 initial model data, are shown. In Fig. 1 *c*, *d* the calculation result for the considering region simulation area is presented – averaged over two models temperature changes in the future climate for 2071 – 2100 years in comparison with the control period of 1971 – 2000 years for winter (December – February) and summer (June – August) seasons. The statistical significance is not shown – overall the computational domain the obtained temperature change values are significant at the 10 % level. In Fig. 2 the air temperature annual change for three region simulation subdomaines, marked by rectangles in the Fig. 1, *c*, is given.

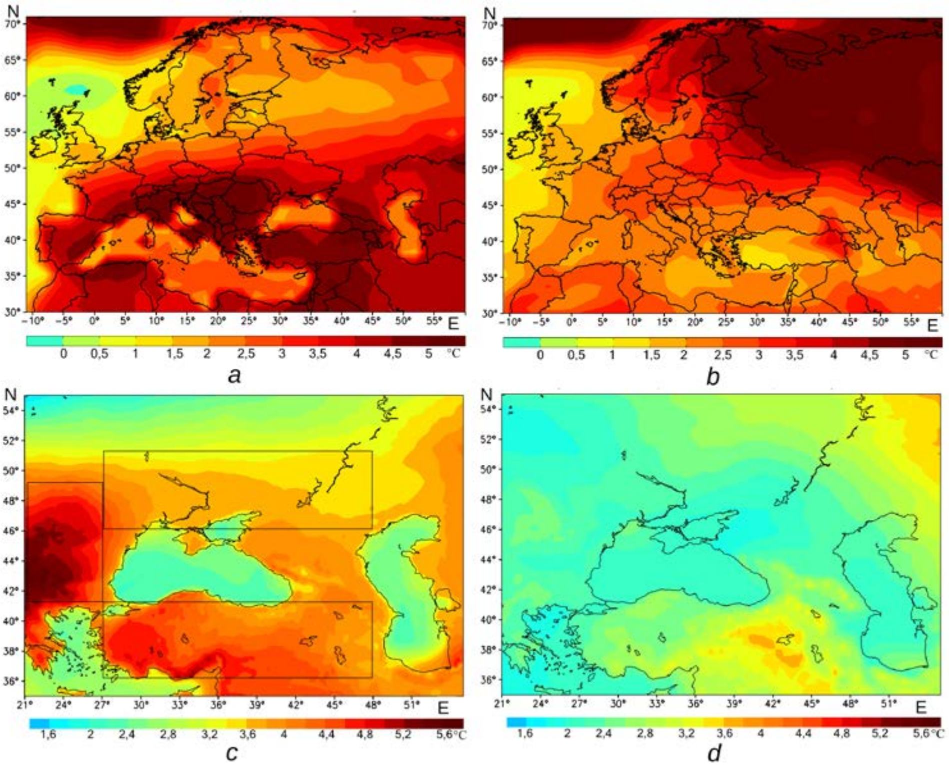

Fig. 1. Surface air temperature change (°C) in the future climate of 2071 – 2100 years in comparison with the control period of 1971 – 2000 years according to the *INMCM*4 model data for winter (*a*) and summer (*b*) seasons and averaged over two regional models for summer (*c*) and winter (*d*)

According to Fig. 1, *a*, *b* temperature regime change is characterized by considerable warming in summer and winter seasons. Also the distribution patterns of temperature changes on the European continent for winter and summer are substantially differ from each other. During the winter season the maximum temperature rise occurs in the central and northern zones of the European part of Russia (at ~5 °C). It is known that such a temperature increase in the northern areas during the cold season is primarily due to the positive feedback effect – in the high latitudes an albedo reduction takes place (because of smaller amount of snow) with the subsequent temperature rise [47]. In Southern Europe and the Anatolian peninsula the warming is just 1.5 – 2 °C lower. In summer, on the contrary, the most intensive warming could be observed in the land areas of Southern Europe and the Mediterranean, which confirms the high sensitivity of these regions to the climate change [48]. For the Black Sea - Caspian region the winter maximum of temperature increase is expressed weakly – only in the northern part of the computational domain (Fig. 2, *a*) the winter extremum is comparable with the summer one. In the Carpathians and on the Anatolian peninsula, as well as in the regions of Southern Europe, the most intensive temperature increase occurs in summer (by 4 – 5 °C).

The temperature increase above the land during the both seasons is sufficiently greater, than above the sea. This result also demonstrates a well-known climate feature – unevenness of warming above the sea and the land, and it leads to some related effects [49, 50]. In general, the obtained temperature change distributions correlate well with the assessments for the global models ensemble [12, 13]: *INMCM*4 model is one of the models which sensitivity (by the ensemble) to the external perturbations is close to the average.

The given climate change distributions for the late 21st century, obtained applying the initial global numerical model, don’t describe the impact of smaller-scale climate forming factors. As it was mentioned, a high spatial resolution in the regional model allows reproducing this contribution more adequately, and its determination could be considered as the most expectable result of the regional simulation. But we shouldn’t expect considerable changes of integral characteristics from the regional models because the model is strictly tied to the input data at the domain boundaries. At the same time, the interior area of domain, where the approach of assimilation in the buffer zone is used, produce their own atmospheric circulation, which takes into account the impact of regional factors. This could be also referred to the projections of climatic characteristic changes: the fields of changes calculated under the regional models (which don’t contradict the fields calculated under the global models) provide the additional information due to the higher resolution.

The calculated atmospheric fields of regional models may differ from the input large-scaled fields even away from the seaside and mountains. That may be caused by differences of physical processes parameterization in global and regional models or by possibility of more small-scaled motion representation in the regional model (in comparison with the global model). For example, in the work [51] it is stated that the regionalization leads to the weakened warming and to the greater precipitation increase as compared to the global model calculation results. The similar effect in the air temperature fields is observed during the calculation by *RegCM*4 (Fig. 2) model. In accordance with this model, the warming in the Black

Sea – Caspian region will be more moderate. During the winter season the air temperature will increase by 2 – 3 °C. The model retains the summer warming

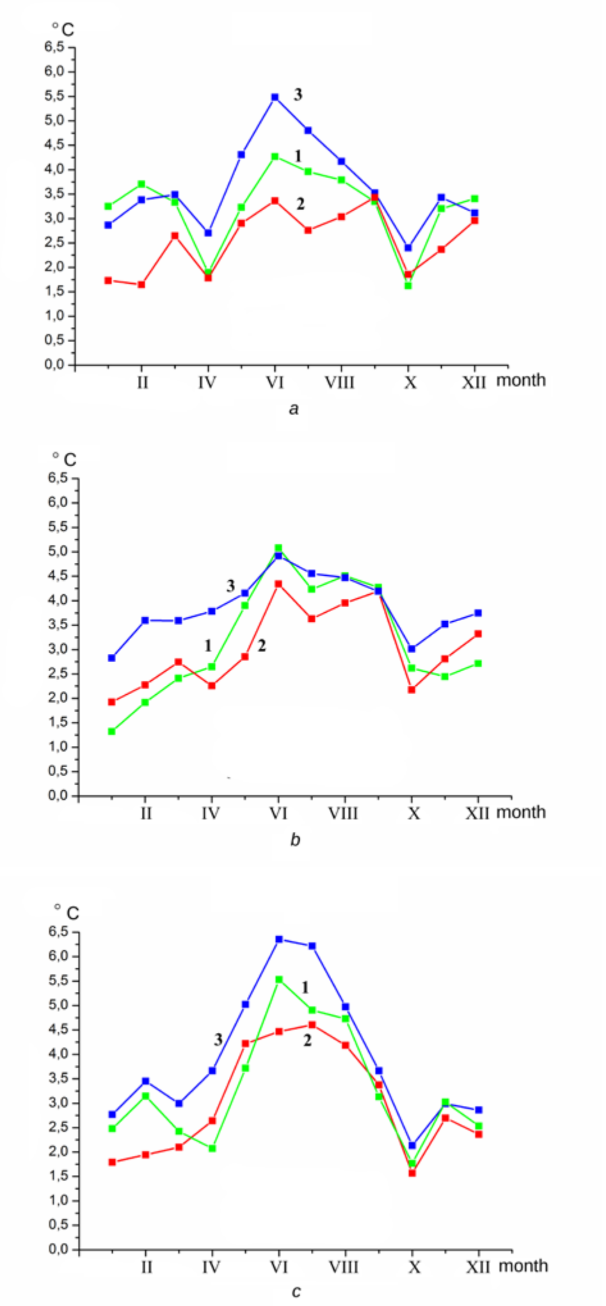

Fig. 2. Annual surface air temperature changes (°C) in a future climate of 2071 – 2100 years in comparison with the 1971 – 2000 years control period, averaged for the northern (*a*) and southern (*b*) subdomaines and for the Carpathian region (*c*) for the *INMCM*4 (*1*), *RegCM*4 (*2*), *HadRM*3*P* (*3*) models

maximum on the Anatolian Peninsula and in the Carpathians repeating the annual temperature changes according the data of *INMCM*4. The largest deviation from the input data using *RegCM4* manifests for the territory of Ukraine and for the southern region of European part of Russia (Fig 2, *a*). A summer warming maximum here is practically absent – the temperature increases just by 3 °C (it's substantially lower, than under the *INMCM*4 and *HadRM*3*P* data).

As a result of the regionalization by *HadRM*3*P* model, there was obtained a significant warming. From Fig. 2 it's obvious that using this model for the northern part of the domain and the Carpathians a pronounced summer warming maximum (similar to the results for Southern Europe) is observed and it is greater, than according to the input data (up to 5 – 6 °C). It is also accompanied by more pronounced precipitation decrease. In mountainous areas of the Anatolian peninsula and the Caucasus, according the *HadRM3P* data, the summer warming is not so considerable as in other regions, it does not exceed the value of 4 – 4.5 °C, as well as according to *INMCM*4 data. On the other hand, according to the *HadRM*3*P* data the temperature increase in this region in summer and winter will be more intensive, than according to other models (by 3.5 – 4 °C).

Thus, under two regional models the Black Sea – Caspian region (Fig. 1, *b*, *c*) is characterized by a significant warming in both seasons with a maximum in the summer period. The greatest summer temperatures increase (5 – 5.5 °C) is observed in the Carpathian Mountains and in the west of the Anatolian Peninsula. To the North and Northeast this increase weakens and in the south of the European part of Russia it amounts 3 – 4 °C. In winter the regional temperature rise is rather uniform (2 – 3 °C). As it was mentioned, throughout the year sea basins act as a factor that reduces the warming by 1 – 1.5 °C. The given estimates are quite close to the ones obtained in the work [5].

The downscaling by two models provides slightly different assessment of temperature climate changes. As it follows from Fig. 2, the model values averaged by the subdomains in one case characterize weakened warming, and in another – enlarged warming in comparison with large-scale assessments. The probable cause of such diversity is the difference in the physical processes parameterization in these two models.

Similar but greater differences are observed in the precipitation calculation. The execution of additional experiments on parameterization schemes of cloudiness and precipitation tuning in order to reduce the mismatch between the models is the issue requiring a special consideration. In our case, for the averaged results of two models the integral estimates appeared to be very close to the input data. This could show the advantages of several model ensemble usages for reproducing the climate and its changes.

Precipitation. One of the most hard-estimated parameters during the analysis of climate change model projections is the precipitation. In comparison with the temperature the spatial fields of annual average and seasonal changes are more complex and unfortunately there is no well consistency of results. That happens because of the fact that precipitation is a diagnostic model parameter. The approaches to the parameterization of precipitation growth in the models are different. As a result, during the regionalization the climate variability of mean and extreme precipitation fields is determined by the choice of the regional model, especially in the summer season [52, 53]. This leads to a strong inter-model dispersion of assessments. When the temperature changes are mainly determined by the global model selection [14], the regional assessments by two models differ insignificantly, but precipitation fields more differ in value and have a higher spatial inhomogeneity.

In Fig. 3 the spatial distribution of precipitation amount changes in the future climate by the global and regional models for two seasons is shown. The precipitation annual change, averaged for three above-mentioned subdomaines, of monitoring and future periods is given in Fig. 4. Unlike for the temperature results presented above, we describe here not just the values of changes. Moreover, for the more detailed consideration of the precipitation annual change features their frequency and intensity were calculated. The frequency of precipitation days was calculated as a relative repeatability of humid days. A common 1 mm/day limit was chosen as a definition of humid day. The intensity was calculated as the average precipitation amount in a humid day. The calculation results of precipitation frequency and intensity are shown in the table. The data are given only for spring and summer, because the changes in the other seasons are insignificant.

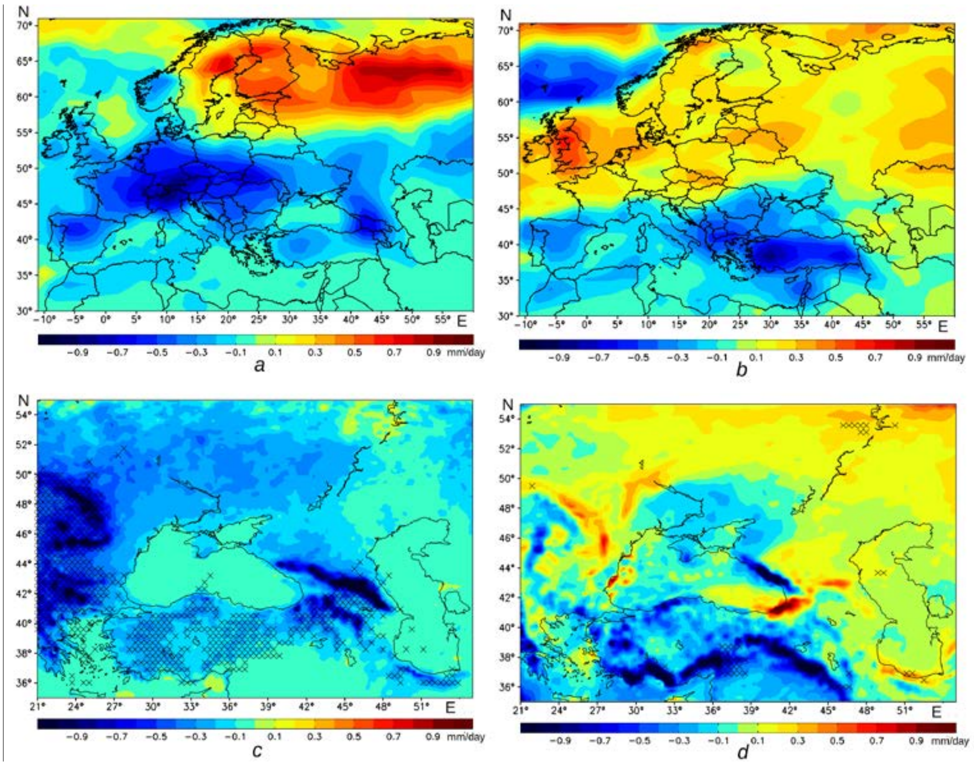

Fig. 3. Precipitation amount change (mm/day) in the future climate of 2071 – 2100 years in comparison with the control period of 1971 – 2000 years in accordance with *INMCM*4 model data for summer (*a*) and winter (*b*) and averaged over two regional models for summer (*c*) and winter (*d*). The points, where the significance criterion is realized, are marked by crosses (for the regional models)

Comparing the precipitation value change distribution under *INMCM*4 (Fig. 3, *a*, *b*) data with multi-model data [12] we are able to make a conclusion about their qualitative agreement. They differ quantitatively because the precipitation distributions [12] are given for the other "moderate" *RCP*4.5 emission scenario, and instead of three-month seasons the semiannual seasons are used. The well-defined precipitation reduction area in Sothern and Central Europe for summer season is shown in Fig. 3, *a*. In Fig. 3 the precipitation amount change is given in mm/day. In relative units [54] the area of precipitation amount reduction will cover the Mediterranean region more than at 50 %. In the relative units the maximal precipitation amount reduction was localized in in the highlands of the Alps, the Carpathians and the Caucasus. A slight increase (up to 30 %) was observed in some areas of northern Europe. The comparison of precipitation amount change by the global model with the results after the regionalization (Fig. 3, *c*, *d*) demonstrates that resolution of *INMCM*4 doesn't allow making a detailed picture of the precipitation anomalies spatial distribution. The usage of regional models allows us to identify the effects, related to the local features of the underlying surface more distinctly.

Change of precipitation frequency (*F*, day^{-1}) and intensity (*I*, mm/day), averaged over the subdomains of the computational domain, in future climate of 2071 – 2100 years in comparison with the monitoring period of 1971 – 2000 years

Region	Parameter	Spring			Summer		
		*INMCM*4	*HadRM*3*P*	*RegCM*4	*INMCM*4	*HadRM*3*P*	*RegCM*4
North	*F*	0.0	–0.036	–0.01	–0.054	–0.081	–0.022
	I	0.004	–0.028	0.072	–0.182	–0.426	–0.029
South	*F*	–0.074	–0.094	–0.078	–0.028	–0.041	–0.032
	I	–0.2	–0.27	0.02	–0.202	–0.492	–0.639
the Carpathians	*F*	–0.07	–0.116	–0.115	–0.121	–0.125	–0.108
	I	–0.276	–0.282	–0.091	–0.585	–0.631	–0.807

In the northern part of the region (Fig. 4, *a*) the changes in future climate are less pronounced. In these areas, in the absence of high mountains and other elements of the relief, the precipitation values (for the data of regional and global models) are the closest to each other, although, according to the regional model, the total amount of precipitation are somewhat lower. The precipitation minimization by *HadRM*3*P* model had been indicated before [44]. In general, the regional models realistically reproduce the annual precipitation change, which corresponds to the continental climate in this area. The amount of precipitation has a clear annual change with a maximum in the spring and early summer, corresponding to the active phase of the spring-summer convection. By August the precipitation amount decreases, its rise occurs only during the cold weather and the increase of large-scaled widespread precipitation. In the future climate the annual variation type remains but the amount of precipitation during the spring-summer period will decline. This decline occurs due to the drop of precipitation repeatability (by 0.05 – 0.10), the intensity changes are insignificant. In winter the precipitation amount remains at the same level.

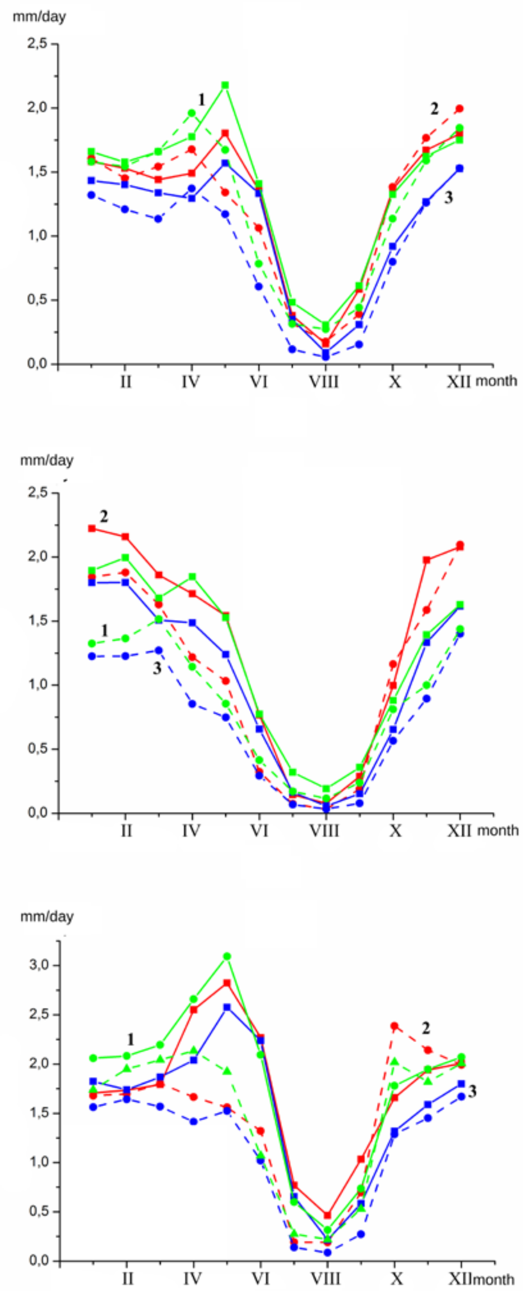

Fig. 4. The annual course of precipitation (mm/day) for 1971 – 2000 year check period (solid lines) and for the future climate within 2071 – 2100 years (dashed lines), averaged over the north (*a*) and south (*b*) subdomaines and the Carpathian region (*c*) for the following models: *INMCM*4 (*1*), *RegCM*4 (*2*), *HadRM*3*P* (*3*)

As it can be seen from Fig. 3, summer decrease in amount of precipitation in the northern regions is not statistically significant (the same is true for the spring). However, it is worth noting an interesting effect in the annual precipitation in the future climate (Fig. 4, *a*) – compared to the control period, the maximum amount of precipitation is shifted from May to April. This demonstrates the process described in the literature [21, 22] and associated with the earlier snow melting in warmer climates. As a result, the evaporation increases and the albedo of land reduces, which contributes to its early warm-up and development of convective clouds and precipitation. Obviously, this effect is realized in all three models (Fig.4, *a*).

On the other hand, summer decrease in amount of precipitation in the Carpathian Mountains and the Anatolian peninsula (Fig. 4, *b*, *c*) is statistically significant, concerted with both regional models and also is shown in the global model. In the Carpathian highlands the summer amount of precipitation decreases by more than 1 mm/day, and in the foothills and in the western Black Sea region - by 0.6 – 0.7 mm/day on average in the two regional models. Analysis the annual variation (Fig. 4, *c*) shows a very significant reduction in the amount of precipitation in this region in the period from March to August, and this effect is found in all three models. The annual variation is close to 1971 – 2000 year control period to the one in the northern part of the computational domain, but is characterized by more heavy precipitation. And as for the 2071 – 2100 year future period spring and summer maximum in this region is virtually leveled, although under the *RegCM*4 model it becomes less than autumn maximum. Note that there is no growth of autumn amount of precipitation in the large-scale model. On average, its reduction in these areas during the summer and spring is greater than 40 %. A similar result was observed for the southern part of the computational domain (Fig. 4, *b*). The annual variation is different from the aforementioned, but the change in the amount of precipitation is comparable to the Carpathian region: while in Fig. 3, *c* summer decrease in amount of precipitation is not so pronounced and in the spring season is 0.7 – 0.9 mm/day (~ 40 %).

According to the table, in the Carpathian region and the Anatolian peninsula spring decrease in the amount of precipitation is mainly due to the decrease of its frequency. The intensity remains practically the same - its average value in these areas is 4 – 5 mm/day. In summer months, the role of decreasing the intensity of the reduction in the total amount of precipitation is somewhat higher than in the spring. Rare summer precipitation in future climate will be less intense (15 – 20 %), yet their frequency decrease is more pronounced – up to 50 % in the Carpathians and 30 – 40 % — on the territory of Turkey.

Taking into consideration the fact that in the area of maximum decrease in the amount of summer precipitation the most intense summer warming also occurs, the region can be regarded as the most visible area of climate change. Similar changes in the amount of precipitation in south-eastern Europe are reproduced with other models. Among the possible reasons, as already been mentioned, is earlier snow melting, leading to increased evaporation in the early spring and the negative anomalies in the moisture content in the soil by the end of spring and summer, and consequently – to evaporation and convective activity decrease during the summer period (maximum shift of the annual course of evaporation). This mechanism works only when the water content in the summer is reduced to a critical value, which will limit the flow of latent heat. A side effect is a change in heat balance at the surface – the increase of the flow of sensible heat, which leads to an increase in temperature and strengthening mechanisms described below.

The second mechanism is related to the uneven heating of the land and ocean. Under the sea air advection on the land and more significant warming in the future climate the more dramatic drop of the relative humidity takes place. Both effects are further enhanced due to the positive feedback between them when the weakening of spring amount of precipitation leads, in its turn, to further soil siccation in summer. Besides, the reduction of cloudiness with relative humidity decrease leads to the short-wave radiation growth and further increase of the temperature.

The main predictor of precipitation formation is the relative humidity, which largely determines their frequency and to a lesser extent – the intensity [22]. The above mechanisms lead to its significant decrease. We shall remind you, that changes in precipitation in these areas generally occur at the expense of their frequency decrease. Relative humidity, according to the regional models, is reduced in these areas in the spring and summer months, by more than 10 %, which is one of the main reasons for decrease of the precipitation occurrence frequency.

To illustrate another, equally important mechanism in the implementation of climate change, the circulation one, we should consider the change in the amount of precipitation in the Black Sea-Caspian region in winter season. Within almost entire area the changes are not statistically significant, but there are several areas of significant changes in precipitation in the mountainous areas - in the Caucasus region, the Taurus Mountains and the Armenian highlands. To analyze the possible cause the spatial variations of the wind circulation averaged over two regional models are given. As it is shown in Fig. 5, *a*, in winter in warmer climates the wind circulation in these areas changes in the direction of the predominance of the northern and north-eastern, but colder and dryer, winds. Obviously, the weakening of the more humid and warm air flow from the South and South-West leads to a decrease of orographic precipitation in these mountain ranges. The similar result was obtained in the work [9]. There is no such effect in the global model; it is the result of regional simulation. Summer change of circulation is also very typical (Fig. 5, *b*) – in fact, an additional anticyclonic vorticity appears in the entire Black Sea-Caspian region. The local anticyclone centered over the Crimean Peninsula is also visible. This fact is important from the viewpoint of the aforementioned mechanisms of the regional summer warming and precipitation amount reducing.

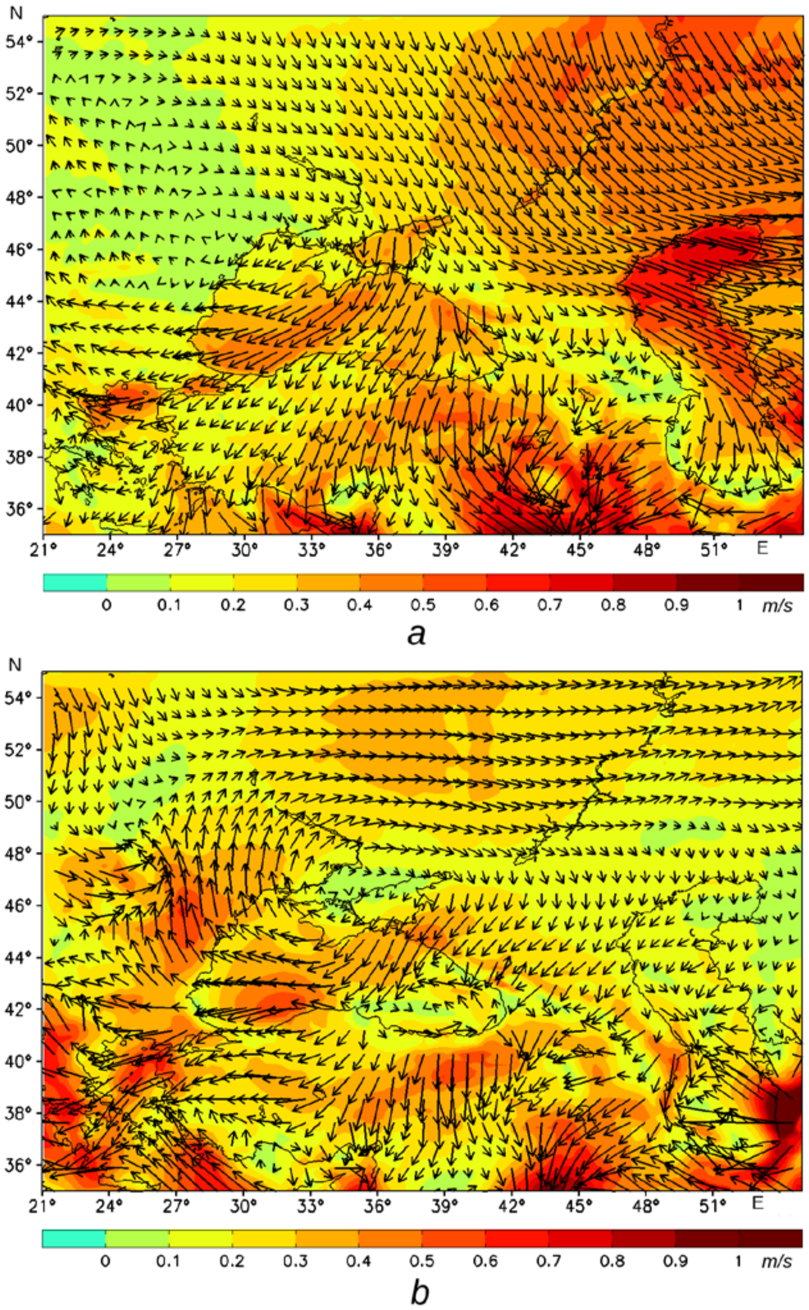

Fig. 5. Changes of the wind velocity (m/s) in the future climate within 2071 – 2100 year period as compared to the 1971 – 2000 year control period, averaged over two regional models for winter (*a*) and summer (*b*). Color show the modules of the wind velocity changes

Conclusion. The paper discusses the results of dynamical downscaling of the data of the atmosphere and ocean *INMCM*4 general circulation model using two models of climate – *RegCM*4 and *HadRM*3*P*. Application of these two models permitted to build regional projections of climate change in the Black Sea-Caspian region, taking into account local topography and underlying surface, and to obtain more detailed physically based assessment of climate change on a regional scale.

The basic parameters of climate change in the Black Sea-Caspian region in the end of the 21st century on the assumption of intense anthropogenic greenhouse gas emissions in accordance with the *RCP*8.5 scenario are given. Change of the climate in the region is characterized by significant warming, more pronounced in summer and relatively mild in winter. The most significant summer warming is observed in the Carpathian Mountains and the Anatolian Peninsula, the temperature increase is about 5 °C. To the North and North-East this warming is getting weaker and in the south of the European part of Russia the temperature increase is 3 – 4 °C. In winter the warming is sufficiently even within the region, the increase is 2 – 3 °C. Sea basins act as a factor that reduces the warming in the coastal areas (for 1 – 1.5 °C). The main feature of the precipitation changes is a significant reduction in their number (over 40 %) in spring and summer in areas with the maximum warming (the Carpathians and the territory of Turkey). Naturally, this trend could have very negative economic and humanitarian consequences. In the both models, the decline of the precipitation amount is due to the reduction of the convective precipitation frequency. Among the main causes of climate change in the future should be noted both thermodynamic phenomena associated with a decrease in the relative humidity and circulation features caused by the enhanced anticyclonic circulation in the region.

An important finding is a good concordance of the obtained numerical evaluations with the data of the previous research. This demonstrates the prospects for further application of the regional models for studying various aspects of the climate of the Black Sea-Caspian region.

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